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MAGMA ENERGY - A FEASIBILE ALTERNATIVE?*

by

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ABSTRACT

This report provides a short review of the work performed by Sandia Laboratories in connection with its Magma Energy Research Project. Results to date suggest that boreholes will remain stable down to magma depths and engineering materials can survive the downhole environments. Energy extraction rates are encouraging. Geophysical sensing systems and interpretation methods require improvement, however, to clearly define a buried magma source.

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MAGMA ENERGY - A FEASIBLE ALTERNATIVE?

Introduction

The world's geothermal energy resources exist in a variety of forms: dry steam, hot water, geopressured water, hot/dry rock, thermal gradients in the earth's crust, and magma. The objective of the Magma Energy Research Project now underway at Sandia Laboratories with U. S. Department of Energy funding is to investigate the scientific feasibility of extracting energy directly from deeply buried circulating magma sources.

Significant amounts of thermal energy must exist in igneous-related systems in the upper 10 km of the crust of the world. In the western United States, Smith and Shaw (1979) estimate that 10^{23} J (10^{5} quads) of thermal energy exist in evaluated young igneous-related systems within the 10 km depth. Of these systems, they estimate about two-thirds probably still have magma chambers with large molten fractions. This energy resource represents approximately 800+ times the total annual energy consumption in the United States. Smith and Shaw further estimate that the extent of thermal energy contained in unevaluated igneous-related systems will be at least 10 times the amount in the systems they evaluated.

Molten magma in the upper crust of the world as a potential source of geothermal energy has been addressed in a number of earlier publications (Colp and Brandvold, 1975; Stoller and Colp, 1978; Hardee and Larson, 1977; Cheng, 1978; Kennedy and Griggs, 1960; Fedotov et al, 1975; Heffington et al, 1977). Colp and Brandvold (1975), Stoller and Colp (1978), and Hardee and Larson (1977) have described the extraction of energy using a heat exchanger inserted directly into shallow magma. Fedotov et al (1975) have discussed the potential energy extraction from a magma body in Kamchatka. Kennedy and Griggs (1960) discuss power recovery from a large, fresh molten lava lake. Heffington et al (1977) have examined the potential for energy extraction from magma in the main chamber of volcanoes. The advantages of direct energy extraction from magma are the high source temperature and the favorable heat extraction rates resulting from induced convection in the molten magma.

There is evidence that some magma chambers exist at depths as shallow as 4 to 5 km in the western United States (Iyer et al, 1979; Eaton et al, 1979, Sanford et al, 1976, Chapin et al, 1979). Basaltic magma chambers with their higher temperatures, lower viscosities, and potential convection offer the best prospect for efficient heat extraction. Although some shallow basaltic chambers are thought to exist in the continental United States at such places as San Francisco Peaks, Newberry, Medicine Lake and others (Decker, 1979; Varnado and Colp, 1978), evidence for large quantities of shallow basaltic magma bodies in the United States is currently lacking. Recent work by Hardee (1980), as described later in this paper, indicates that the more plentiful andesitic and wet granitic magmas also appear to offer promising convective heat transfer rates.

Any program devoted to tapping the energy of a buried magma source is considered long term and high risk because of the technological problems to be solved and the many unknowns to be explored. The program at Sandia is emphasizing the investigation of basic scientific and engineering questions of energy extraction from magma. It is not structured toward early on-line power production.

Project Organization and Progress

The Sandia Magma Energy Research Project has been divided into five discrete tasks.

Task 1 - Source Location and Definition

It is imperative that the existence of a magma source, its depth, areal extent, and general form (whether in a finite pool or in a honeycomb of crevices filled with molten material) be known with the greatest degree of certainty before proceeding with plans for source tapping.

A few studies have been conducted to locate and identify a buried magma source; most of the existing remote sensing methods have been used--seismic, microseismic, resistivity, gravity, magnetic, magneto-telluric, infrared, and thermal. The USGS has examined areas under Yellowstone National Park (Eaton et al, 1979); Long Valley, CA; Kilauea Volcano, HI; Geysers/Clear Lake, CA (Iyer et al, 1979); and other locations in the western United States.

Sensing Studies. Sandia conducted a Molten Lava Sensing Experiment in March 1976. The still-molten lens in Kilauea Iki Lava Lake (a prehistoric pit crater located in the Hawaii Volcanoes National Park which was partially filled with lava during a 1959 eruption) was selected as the experiment site. The objective of the experiment was to develop techniques for locating magma. In particular in the lava lake, an attempt was made to define the areal extent, the depth, and the thickness of the molten lens using sensing methods: active and passive seismics, electrical resistivity, active electromagnetics, audio magnetotellurics, and temperature gradients.

Professor John F. Hermance, Brown University, has made a critical assessment of the sensing experiments conducted on Kilauea Iki lava lake (Hermance et al, 1979). Figure 1 shows horizontal and vertical models of the lava lake resulting from a preliminary analysis of the experimental results taken from his report.

The information required to evaluate the accuracy of the sensing systems in identifying and defining the molten rock lens and to verify the models derived had to be obtained by drilling. Sandia performed two lava lake drilling programs whose objectives were to penetrate the molten lens of Kilauea Iki and obtain the data required to evaluate the sensing studies data.

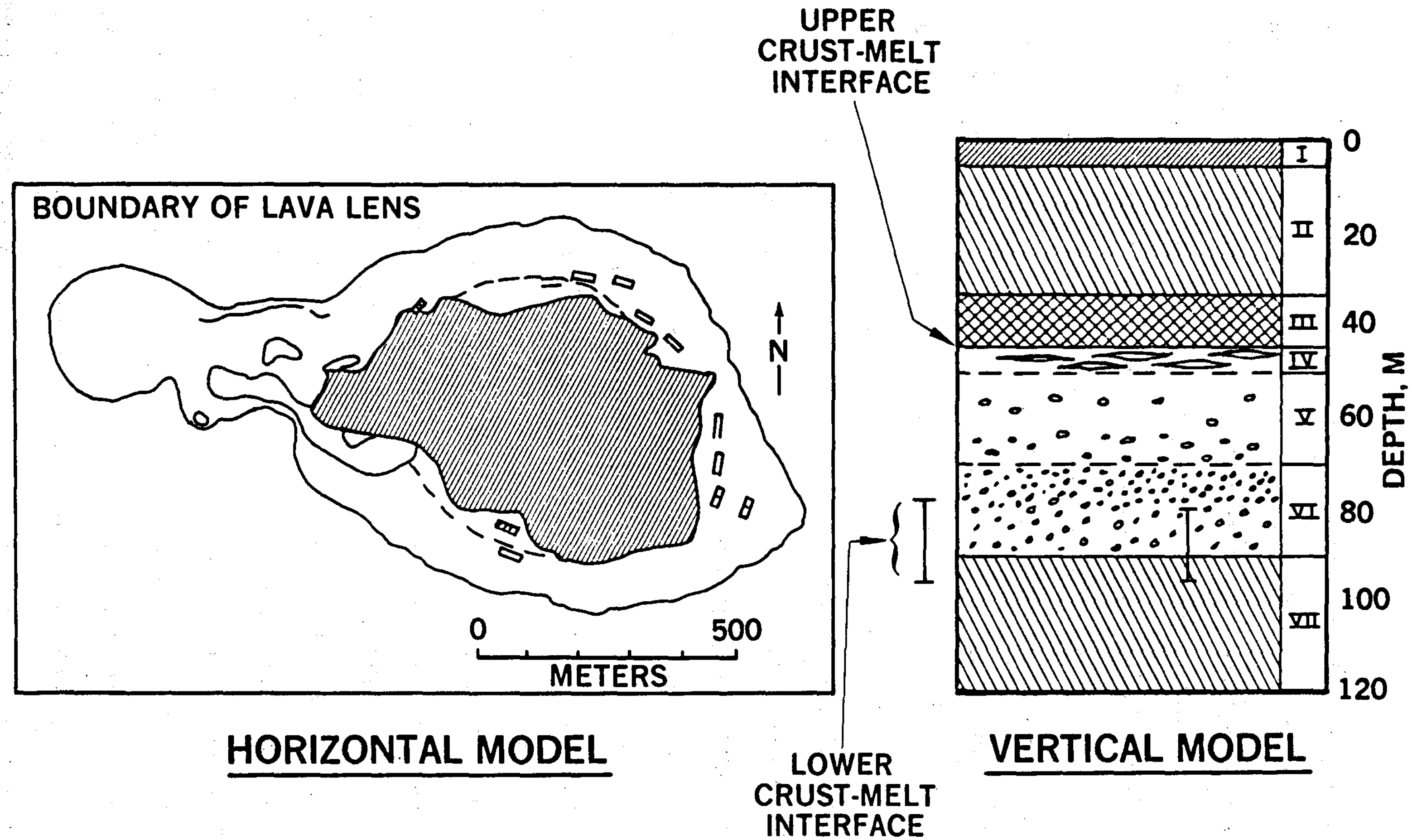

Figure 1. Models of Kilauea Iki Lava Lake from Preliminary Analysis of 1976 Sensing Experiment Data (After Hermance et al, 1979).

The first drilling program was performed in FY 1976, using conventional, water cooled drilling equipment. After penetrating 60 cm into a fluid molten rock, an unexpected solid obstruction prevented further drilling.

The second drilling program was performed in FY 1979. An advanced drilling system capable of drilling through a solid obstruction while the drill stem was surrounded by fluid molten rock at 1070°C (Colp and Traeger, 1979) was designed and laboratory tested. This system was not used because an appreciable thickness of fluid molten rock was not encountered. Conventional HQ-size (96 mm diameter) core drilling equipment using water for cooling and cuttings removal was used to successfully drill to a depth of 10 m during initial entry into the 1052+°C melt-crystal suspension lens that was encountered. Conventional methods were less reliable when reentering drill holes filled with glassy flow-back rock. Specially designed water jet-augmented drag and core bits were needed to drill reliably into the glassy flow-back rock and through fluid molten rock veins (Neel et al, 1979).

FY 1979 drilling and thermal studies in the lava lake show that the lake is in a late stage of solidification, with no low-viscosity lens, but rather a plastic, multiphase region of crystals (mainly olivine) in melt with intermittent, thin (1-4 cm?) veins of very fluid molten rock. Models were developed and verified for predicting the thermal behavior of the lava lake geothermal system and estimating the solidification state of the multiphase lens (Hardee and Larson, 1979; Hardee, 1979).

Petrographic studies of the Kilauea Iki cores indicate that disequilibrium mineral assemblages presumably reflecting high chill rates are present; in-situ crystallization as well as crystal settling plays a role in the observed differentiation; and 35 to 40% liquid phase remains in the melt-crystal suspension lens.

Task 2 - Source Tapping

The Magma Energy Research Project has addressed the physical characteristics of a hole drilled through the roof rocks overlying a magma source. The main concerns are whether those rocks fail in a brittle fashion under in-situ temperature and pressure so that they can be drilled by conventional methods, and whether the borehole will stay open after drilling to allow the insertion of energy extraction equipment. A continuing laboratory research contract with the Center of Tectonophysics, Texas A&M University, to investigate these concerns has been underway since 1974. Friedman et al (1979) presented a summary of past work on this contract.

Borehole Stability. Strengths of dry andesite, basalt, granodiorite and obsidian were determined to 1050°C at confining pressures of 0 and 50 MPa. The three crystalline rocks were essentially brittle throughout the P-T ranges investigated until partial melting occurred. Boreholes filled with a fluid having a density equal to that of water are stable to depths of 5 km for basalt and greater than 10 km for granodiorite at temperatures in the range of 900-1000°C. Open boreholes cooled to 400°C are stable in both materials to depths of 10 km.

Current experimental runs on water-wet charcoal granodiorite to evaluate possible water-weakening effects fail to indicate any. It may be found that at the low pressures of interest to the project, water-weakening is minor. A current analysis of the dry fracture strengths of the three crystalline rocks shows that at temperatures between 700 and 1000°C the Coulomb-Mohr failure criterion can be used to estimate the instantaneous failure of boreholes.

Task 3 - Magma Characterization

Definition of chemical and physical properties of magma is necessary to interpret results from geophysical sensing techniques, to estimate energy extraction mechanism and rates, and to evaluate materials compatibility. Since fugative gases significantly affect properties, studies must be made on materials simulating in-depth compositions. Consequently, efforts of this task are (1) to predict in-situ compositions using analyses of gases from volcanic eruptions and (2) to measure properties of simulated systems at in-situ conditions.

Magmatic Volatiles. Volatiles have a strong effect on several magma properties, such as crystallization temperatures, viscosity, density, electrical resistivity, etc. In order to predict in-situ fugative concentrations, reported volcanic gas analyses have been adjusted for sampling errors to put them on a consistent basis and subsequently have been thermodynamically folded to in-situ conditions.

Data for approximately 150 volcanic gas analyses of collections taken at high temperatures (> 950°C) in source regions of tholeiitic and alkaline mafic lavas (Hawaii, 1913-19, Nyiragongo, 1959; Surtsey, 1964-67; Etna, 1970; Erta Ale, 1971-74) have been studied. These "high quality" volcanic gas samples exhibit erratic chemical characteristics.

Computerized thermodynamic stuides have been used to correct these gas analyses for errors from atmospheric contamination; addition of meteoric H_2O; condensation and re-evaporation of S and H_2O in lead-in tubes; reactions between erupted gases and metal sampling equipment; oxidation of minor species (S_2, H_2S, H_2, CO); incomplete chemical analyses; and analytical errors in H_2O determinations.

The restored analyses (Gerlach, in press a, through in press e) provide a basis for several observations and inferences:

(1) Volcanic gases are erupted in a state closely approaching chemical equilibrium.

(2) After removal of sampling errors, apparent short-term variations (minutes-hours) virtually disappear, implying that meaningful data can be obtained over relatively short periods of observation.

(3) Long-term variations (months to years) are apparent in some series of restored analyses; they are mainly due to differences in CO_2 content and reflect the relatively low solubility of CO_2 in silicate melts.

(4) The restored analyses of gases collected from tholeiitic lavas (e.g., Erta Ale) are characterized by high H_2O contents (70-90 mole %). Those from alkaline lavas (e.g., Etna and Nyiragongo) are characterized by lower H_2O (45-50 mole %) and relatively high CO_2 (25-50 mole %).

(5) The total sulfur content (SO_2, S_2, H_2S) of volcanic gases appears to be in large part a function of the O_2 partial pressure of the outgassing lava.

Magma Simulation Facility. A laboratory study is underway to measure the effects of pressurized volatile atmospheres on the physical properties of molten rocks, and to examine selected aspects of the chemical equilibria between silicate melts and a gas phase. A schematic drawing of the Magma Simulation facility designed and built at Sandia is shown in Figure 2. The pressure vessel can be operated at pressures up to 4 kbar and maintain a cylindrical hot zone of 10 cm length and 10 cm diameter at constant temperatures up to 1600°C. The facility is currently being used to study crystallization phenomena.

Current active experiments under development include viscosity measurements using a falling sphere viscometer, electrical conductivity measurements, and acoustic velocity measurements. Other geoscience experiments proposed include the study of rhyolite/basalt/andesite interface reactions at various pressures and temperatures, and physical property studies involving volatile-containing silicate melt, including highly reactive gases.

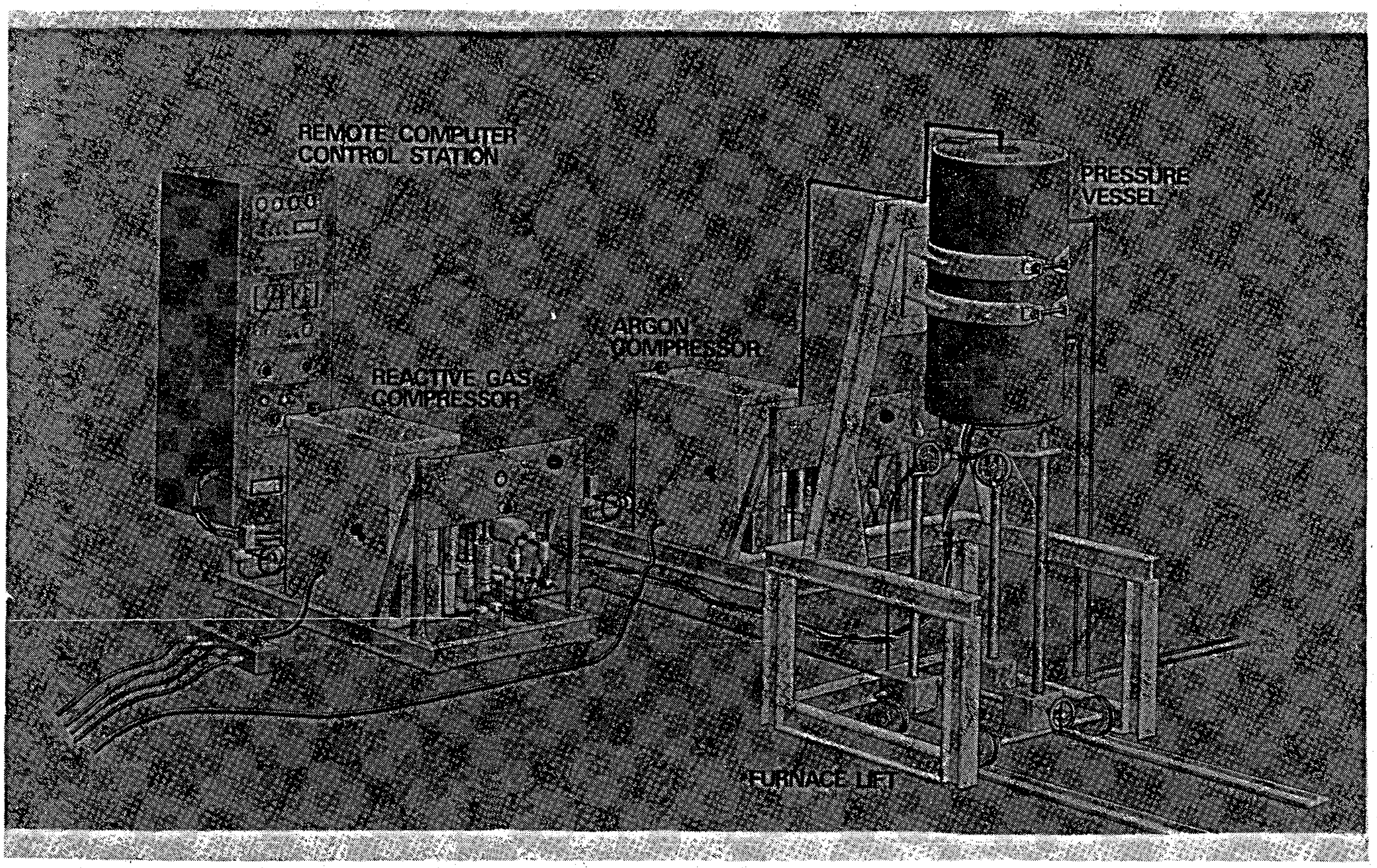

Figure 2. Artists Drawing of the Sandia Magma Simulation Facility.

Task 4 - Magma/Material Compatibility

In a magma energy-utilization application, engineering materials will be expected to perform in three different environments, ranging from near-surface to magma. The conditions and associated problems of these environments are shown in the table below.

Magma/Metal Environments

Environment (Location)	Conditions	Problems
1. Near Surface	Low temperature (150°C) oxidizing, H_2O rich gas	Oxidation corrosion
2. Hydrothermal Region	Moderate (150°-500°C) temperature, oxidizing, corrosive hydrothermal brines	Oxidation and brine corrosion
3. Magma	High (600°-1250°C) temperature reducing, high sulfur	Sulfidation, corrosion, thermal strength degradation, metal dissolution

Note: Studies of material performance in environments 1 and 2 are currently underway at a number of laboratories as part of the development of hydro-geothermal energy sources.

Near Surface Environment. Metal samples have been exposed to fumarolic gases from various vents in Kilauea volcano, Hawaii, as part of a continuing study. In general, stainless steels are attacked fairly rapidly in the fumarole environment, while nickel-base alloys such as Inconel, Rene-41, and Hastelloy-C are resistant.

Magma Environment. There are two major areas of concern in the survival of a metal heat exchanger immersed in a buried magma source. The first is survival during a loss-of-coolant shutdown when the temperature of the unprotected heat exchanger can reach the ambient temperature of the magma - 1000 to 1250°C. It is likely that such an emergency shutdown will be of relatively short duration - a few hundred hours. The second area of concern is for the heat exchanger survival during normal operating conditions. At this time the temperature of the heat exchanger will be controlled so as to not exceed 500-600°C.

Its exterior will be protected further by the glassy coating formed during its normal operation in the molten rock. The design life of the heat exchanger under normal operating conditions is 30 years.

A laboratory experimental program is currently underway to study the compatibility of bare metals with both molten rock (magma) and gases dissolved in molten rock - the first concern above. Chemical reactions between magmatic volatiles and metals is of particular interest.

The initial phase of the experimental program involved the study of fifteen pure metals in molten, tholeiitic basalt at 1150°C for 24 and 96 hours (Douglass and Healey, 1979). A cover gas was used to simulate the gas dissolved in magma bodies, having an oxygen fugacity of 9.8×10^{-10} and a sulfur fugacity of 7.0×10^{-3}. Later studies are planned for a number of metal alloys.

Work performed to date has shown that there may be sufficient corrosion resistance to meet the anticipated lifetime of magma energy plants if they become a reality. Although the work is far from complete, certain trends are emerging, and a number of areas for additional research have become apparent. The preliminary trends noted (Douglass, 1979) thus far are:

1. The chromium content of both ferritic and austenitic stainless steels is the most important factor in providing corrosion resistance.
2. The nature and morphology of the corrosion products change with time.
3. There appears to be a difference in the behavior between commercial ferritic stainless steels and high-purity iron-chromium alloys.
4. A synergistic effect of chromium and nickel may exist in the austenitic alloys in providing corrosion resistance.
5. Molybdenum is a potentially good addition for imparting corrosion resistance.

6. Iron-chromium alloys are generally better than cobalt-chromium alloys which are better than nickel-chromium alloys.

Task 5 - Energy Extraction

Molten magma bodies offer a source of high quality, pollution free thermal energy. A number of schemes for energy extraction have been considered, including thermionics, thermoelectrics, steam generation for conversion to electricity, hydrogen production, and generation of synthesis gas (H_2, CO, CH_4). The last three extraction schemes (steam, hydrogen and synthesis gas) were chosen for these scientific feasibility studies, since thermodynamics and surface processing technologies are well defined. The basic questions of energy extraction are then questions of heat and mass transfer rates in and from magma bodies. Definition of the properties of molten magmas (Task 3) is critical to understanding energy extraction limits. Efforts in the Energy Extraction Task have been aimed at limited studies on the dynamics of magma bodies, extraction rates from molten lavas, and preliminary studies on the internal dynamics of heat exchangers. Further information on past work can be found in Colp and Traeger (1979).

A small, single-tube boiler to study heat extraction from a molten-lava source has been tested in 0.2 m^3 of Hawaiian tholeiite lava in an induction furnace (Hardee and Fewell, 1975). The two test runs showed that high heat-extraction rates (100 kW/m^2 to 300 kW/m^2) could be obtained from a molten-rock source. Corrosion or failure of the heat exchanger due to corrosive thermal effects was not a problem, even though the temperature of the molten-lava core (1450° to 1650°C) was well in excess of the melt temperature of the heat exchanger. The test data verified previous assumptions in the heat-transfer calculations, particularly in the convection calculations and the calculations of the thermal transient insertion. The test demonstrated that useful amounts of thermal energy in the form of high quality steam can be extracted from a molten-lava heat source.

Currently, improved convective heat extraction calculations have been completed for several types of magmas (Hardee, 1980). These calculations have included corrections for high Prandtl-number fluids, cylindrical geometry and crust formation. The effect of the high Prandtl number and cylindrical geometry corrections is a moderate increase (20%) in the expected convective heat flux. The formation of a large cylindrical crust of solidified magma on the heat exchanger results in a favorable geometrical situation which increases the effective heat flux at the heat exchanger surface by a factor of 2 to 20. Typical heat extraction rates for a 25 cm radius vertical heat exchanger in shallow basaltic magmas range from 15 to 50 kW/m^2 (20-80 MW per well). More plentiful andesitic and wet granitic magmas are predicted to offer heat extraction rates in the range of 5-25 kW/m^2 (8-40 MW per well). Laboratory tests are currently underway to measure convective heat fluxes, particularly the laminar basalt case.

Fuels Generation. Thermodynamic calculations and experimental studies of the potential of magma and hot rock for the production of fuels (H_2, CO, CH_4) indicate that fluids containing one to three mole percent hydrogen are possible from the interaction of water with typical basaltic magma or hot rocks in the temperature range 1300° to 600°C. Fuel production can be enhanced by addition of organic matter to the injected aqueous fluid (Northrup et al, 1978).

Final Remarks

The results of the work accomplished to date suggest that boreholes will remain stable down to magma depths, engineering materials can survive the downhole environments, and energy extraction rates are encouraging. However, significant improvements in the ability of geophysical sensing systems and interpretation methods to clearly define a buried (5-10 km deep) magma source are needed. To achieve these improvements and to better define energy extraction rates, a more complete understanding of the physical properties of molten and multi-phase magma systems - especially the effects of volatiles on these systems - is required. The direction and emphasis for the Project over the next three to five years will be in these areas.

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